1. Investigators

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2. Title of Research Grant

Retrieval of Cloud Properties and Direct Testing of Cloud and Radiation Parameterizations using ARM Observations (**Grant DE-FG02-90ER61071**).

3. Scientific Goals of Research Grant

The primary goals of the ARM program continue to be improvement of atmospheric radiative transfer and our understanding of the radiative properties of clouds, as well as better representation of clouds and radiation in global climate models. We are addressing these interests within the ARM program in three related research efforts. The first effort is to provide more reliable best estimates of the microphysical and macrophysical properties of clouds by evolving the active remote sensor cloud products generated from data obtained at the ARM central facilities, concentrating on the millimeter-wave cloud radar products and their interface with cloud products from other ARM instruments, such as the Raman lidar, and by developing spectral capabilities on the ARM millimeter-wave cloud radars to advance ARM cloud microphysical retrievals. A second, and related, effort will be to assess the feasibility of retrieving cloud properties at the boundary facilities in the absence of a millimeter-wave cloud radar. Finally, with the aid of best-estimate cloud properties from the ARM active remote sensors, we will evaluate the cloud parameterizations used in large-scale and cloud-resolving models while developing and evaluating a radiative transfer parameterization in the context of these same two types of dynamical models.

4. Accomplishments in "Bulletized Form"

•**A** *Finished the scientific and software development of the* **A***ctive* **R***emote* **S***ensing of* **Cl***ouds (ARSCL) Value Added Procedure (VAP) [Clothiaux et al. 1999, 2000]. Delivered the ARSCL VAP code to the ARM infrastructure as an operational code.*

•**B** *Finished the software implementation of the* **S***hort***w***ave* **F***lux* **Anal***ysis Value Added Procedure (VAP) [Charles Long, personal communication]. Delivered the SWFANAL VAP code to the ARM infrastructure for their final development as an operational code.*

•**C** *Reported all lessons learned in this prototype VAP code development to the ARM infrastructure as two unsolicited documents [Clothiaux and Turner, 2000; Turner and Clothiaux, 2000].*

•**D** *Provided ARSCL-like products to many ARM-supported research teams in support of their research [Boehm and Verlinde, 2000; Hinkelman et al., 1999; Kato et al., 2000; Mace et al., 2000; Marchand et al., 2000; McFarlane et al., 2000; Min et al., 2000]. Operational ARSCL products for April and May 1999 are being provided to Jean-Jacques Morcrette in support of ECMWF reanalysis studies.*

•**E** *Boehm and Verlinde [2000] used ARM TWP-Nauru radiosonde data and results from a micropulse lidar cloud masking routine [Clothiaux et al., 1998] applied to ARM TWP-Nauru data to demonstrate that the large scale lifting hypothesized by Boehm et al. [2000] is potentially responsible for tropical cirrus maintenance.*

•**F** *Demonstrated the feasibility of deconvolving millimeter-wave cloud radar Doppler spectra to estimate cloud particle size [Babb et al., 1999; Babb et al., 2000].*

•**G** *Measured the impact of the current spectral DSP that averages consecutive spectra. Simulations show that such averaging artificially broadens spectra resulting in erroneous retrievals. A new approach is being developed to minimize this error.*

•**H** *Participated in demonstrating the improved accuracy of James Liljegren's new liquid water path retrievals using microwave radiometer data [Liljegren et al., 2000].*

•**I** *Theoretical demonstration of a new technique for inferring time series of optical depths for overcast and broken boundary layer clouds [Barker and Marshak, 2000].*

•**J** *Assembled data from all active sensing instruments in the Southern Great Plains area, including NOAA NexRad and Wind Profiler data, into a uniform format in preparation for cloud studies at the ARM SGP boundary facilities. Currently testing multi-sensor cloud retrieval algorithms that use wind profiler data as the principal active remote sensor.*

•**K** *Designed MM5 model domains/configurations and performed preliminary benchmark (clear-sky) simulations during July 1997 over the ARM-CART site using 36-, 12- and 4-km model resolutions and an improved soil moisture intialization derived from an "offline" (i.e., external to MM5) integration of a land surface model forced by observations.*

5. Accomplishments and Progress in "Extended Form"

We will describe our progress and accomplishments to date in terms of our three stated scientific goals in section 3 and the bullets in section 4 of what we think are our most notable achievements to date. Note that all references in the discussion to follow have contributions from one or more members of our ARM proposal team and are listed in sections 7-9 below.

Provide more reliable best estimates of the microphysical and macrophysical properties of clouds by evolving the active remote sensor cloud products generated from data obtained at the ARM central facilities, concentrating on the millimeter-wave cloud radar products and their interface with cloud products from other ARM instruments.

An evolving theme of the ARM program is the necessity of operationally implementing algorithms developed by its science team. We have taken this message to heart and are currently trying to push our scientific algorithms for processing of ARM active remote sensor data to the point where they can be run by members of the ARM infrastructure. The articles by Clothiaux et al. [1999, 2000] describe in detail the approach that we have taken. We have now delivered to the ARM infrastructure the scientific code that we have developed to implement the approach (**•A**) and have spent many hours first with David Turner, and now Robin Perez, transitioning the code to a semi-autonomous operational state.

Two aspects of this transition have been extremely time-consuming. First, we have evolved the code ourselves to a form that the ARM infrastructure can run in its environment, thereby alleviating ARM infrastructure members of the even more time-consuming task of recoding something that they have not written. And second, we have taken the position that reprocessing of the active remote sensor data to Level A1 in as near a flawless condition as possible is a prerequisite before we process it through our algorithms. Although this has taxed members of the ARM infrastructure, they are slowly working their way forward through the data. To date, we have just about finished processing the TWP-Nauru data from November 1998 through March 2000, and we have recently begun processing/reprocessing the SGP-Central Facility data. We will continue on this effort until all four sites are up-to-date and processing of current data on a monthly basis is progressing smoothly.

To support future ARM VAP efforts we have communicated what we have learned in ARSCL VAP development work to the ARM infrastructure [Clothiaux and Turner, 2000; Turner and Clothiaux, 2000] (**•C**). We will continue to support ARM VAP efforts as requests from the ARM infrastructure arise.

We have attempted to interface with members of other ARM science teams in order to facilitate their use of ARSCL-like data (**•D**). This is turning out to be quite a rewarding experience, as we are learning both a great deal about their scientific interests and about second-order problems in the ARSCL VAP products that we must attempt to address in future research. Within our own research team, Boehm and Verlinde [2000] have used the lidar components of the ARSCL VAP products to test a hypothesis of theirs on tropical cirrus maintenance (•**D**). We are attempting to spread ARSCL data beyond the ARM science team and have recently sent ARSCL data for April and May 1999 to Jean-Jacques Morcrette at ECMWF in his analysis of ECMWF model output.

An important step towards the advancement of our research stated as our second and third goals is the capability to 1) accurately locate clouds in the atmosphere, 2) obtain accurate liquid/ice water paths for them, 3) estimate their optical depths, and 4) assign sizes and shapes to the particles that compose the clouds. The ARSCL VAP (•**A**) goes a long way towards completing step 1). To address steps 2) and 3) we have confined ourselves to liquid water clouds and have recently completed our first efforts of addressing these two points. We have worked with Jim Liljegren [Lijegren et al., 2000] to demonstrate that his new retrieval algorithm removes many of the biases in the early ARM retrievals (•**H**). Importantly, his new retrieval requires ARSCL-like products in order to estimate the cloud liquid water temperature. Once the the ARSCL VAP processing is up-to-date, we will use these VAP data and work with Jim Liljegren to implement his new liquid water path retrieval at all sites. Our model for the implementation of this new liquid water path as a VAP will be identical to the approach that we took in implementing Chuck Long's shortwave flux analysis code as a VAP (•**B**).

In terms of cloud optical depth retrievals Alexander Marshak developed an idea that Barker and Marshak [2000] have now turned into a novel retrieval of low-level cloud optical depth using ground-based zenith radiance measurements at 0.65 and 0.80 $\mu\mathrm{m}$ (•**I**). An important element of their retrieval is differencing these two radiances in order to remove the contribution to the radiance of those photons that have not interacted with the surface. Importantly, this new approach works for clouds ranging from stratus to fair-weather cumulus, thereby vastly expanding the scope of the stratus retrievals developed by Dong et al. [1997, 1998, 2000].

Develop spectral capabilities on the ARM millimeter-wave cloud radars to advance ARM cloud microphysical retrievals.

Our approach to step 4), assigning sizes and shapes to particles that compose clouds, is taking place within the context of millimeter-wave cloud radar Doppler spectra [Babb et al., 1999, 2000] (•**F**). The ARM program is developing a capability to save high time resolution spectra, which we believe is a prerequiste for separating cloud and precipitating particle contributions to radar pulse returns. The developments of this capability by ETL for ARM recently hit a snag when Radian, a subcontractor to ETL on this project, lost an engineer on this project.

To compensate for the current lack of ARM data, Verlinde and Babb have collected a high-time resolution data base of Doppler radar power returns both from ETL (ASTEX experiment) and Roger Marchand (ARM Spring 2000 Cloud IOP) with which to begin their investigations. A first result of theirs (**•G**) is that even over periods less than approximately 1-2 s there are signficant shifts in the mean Doppler velocity, at least in the data that they have analyzed. Consequently, estimates of Doppler spectral width from averages of spectra for more than a few seconds may have a changing velocity component to it, as well as a sub-resolution volume turbulence component. If such a result proves to be robust, retrievals that incorporate spectral width must be re-visited in order to make sure that shifts in the mean Doppler velocity during the spectral averaging period are not destroying the assumptions inherent in the retrieval.

To more fully understand what can be retrieved from high-time resolution Doppler spectra we need access to such spectra over many cloud conditions for extended periods of time. We will continue to work with the ARM infrastructure in support of their efforts to enhance the processing power of the ARM millimeter-wave cloud radars. We anticipate making steady progress during the second year of our proposed research, but hope to gain significant momentum in the third year when the possibility of high-time resolution ARM radar data appears to be a real possibility.

Assess the feasibility of retrieving cloud properties at the boundary facilities in the absence of a millimeter-wave cloud radar

Although the ARM millimeter-wave cloud radars can detect collections of particles with reflectivities as low as -50 dBZ, there comes a point when the cloud particles become too small for these radars to detect. A class of radiatively important clouds with small particles far from the radar are mid-level clouds, such as altostratus. We have seen periods of isolated altostratus that the ARM millimeter-wave cloud radars have completely failed to detect. For isolated altostratus, this is not too problematic as the ARM lidars readily detect these clouds. However, during multi-layered cloud events, when low-level stratus completely extinguishes the ARM lidar beams, mid-level altostratus may go completely undetected by the ARM active remote sensing instruments.

An idea that has floated around in the radar literature for some time is the notion that enhanced moisture fields within a cloud may produce enhanced Bragg scatter that a longer wavelength radar may be able to detect. Miller et al. [1998] investigated this idea using WSR-88D data and found some evidence to support enhanced Bragg scatter. Miller has now collected wind-profiler data from the ARM SGP central facility, as well as the SGP boundary facilities, together with ARM data from these sites in order to further pursue this line of research (**•J**). The approach here is to finalize the development of cloud detection algorithms using Bragg scatter at wind-profiler wavelengths (**•J**) and to test their skill against those clouds detected by the ARSCL VAP instruments at the SGP central facility.

The first cloud type that we will consider in these analyses will be altostratus detected by the ARM lidars, but missed by the ARM radars. If the wind-profiler based algorithms show skill in these tests, they will be incorporated into the ARSCL VAP processing. If the wind-profiler based algorithms show overall skill in detecting other cloud types readily detected by the ARSCL VAP instruments, they will be fully evaluated at the SGP central facility and then implemented at the boundary facilities. Statistics of the cloud data produced at the boundary facilities will then be produced in an attempt to characterize cloud properties at the boundary facilities.

Testing of the first-generation, wind-profiler cloud detections algorithms is contingent upon their completion, as well as completion of ARSCL VAP processing of the SGP central facility data. We expect this to occur in the first six-month period of the upcoming year, with extensive evaluation of the wind-profiler algorithms taking place in the second six-month period.

Use ARM-derived cloud properties to evaluate cloud parameterizations used in large-scale and cloud-resolving models while developing and evaluating a radiative transfer parameterization in the context of these same two types of dynamical models.

Our proposed model research consisted of two components: testing model cloud parameterizations using ARM data and incorporating the gamma-weighted two stream model in cloud-resolving and large-scale models. The first aspect of our research, testing model cloud parameterizations using ARM data, is contingent upon the ARSCL VAP processing of the SGP data and implementation of the improved Liljegren liquid water path retrieval. Consequently, we will not pursue this task until at least the second six-month period of the upcoming year.

To implement the gamma-weighted two stream radiative transfer model in a fairly high-resolution model we have chosen to work with the MM5 model. The nature of this research is two-fold: evaluate performance of the gamma-weighted two stream radiative transfer model against exact three-dimensional Monte Carlo radiative transfer simulations through existing 1-km resolution MM5 cloud fields and implement the gamma-weighted two stream interactively within the MM5 model.

Recently, we have identified an extensive database of 1-km resolution MM5 model runs and we are attempting to acquire the cloud data from these runs. We may also use small samples of 1-km resolution data generated at Penn State to begin our analyses. The goal will be to extensively evaluate gamma weighted two stream heating rates against exact calculations over a wide range of cloud conditions.

To implement the gamma-weighted two stream model interactively within the MM5 model, we have chosen to work with a case study period in and around the ARM SCM cloud IOP of July 1997. To this end Stauffer first is performing MM5 model simulations for generally clear-sky conditions over the ARM-CART site. A weak-forcing, cloud-free case (12 July 1997) is being used as a benchmark for evaluating MM5 skill for producing the diurnal cycle and planetary boundary layer structure around the ARM-CART site as a function of model initial/boundary conditions and model resolution. Our ongoing model experimentation will include more meteorologically complex cases over the ARM-CART site (e.g., shallow and deep convection, precipitation and frontal dynamics). Stauffer has also produced improved soil moisture data (compared to the default climatological values) for MM5 model initialization for the entire month of July 1997 by building an "offline" (external to the MM5) land surface model (LSM) pre-processor which provides 3-hourly soil moisture data for the outermost MM5 domain. In this application, the LSM is forced by observed surface conditions and precipitation. These temporally varying, heterogeneous soil-moisture conditions allow the MM5 to produce more realistic diurnal cycles and planetary boundary layer structures through this period, as revealed by direct comparison against in-situ ARM-CART rawinsondes and remotely sensed data. We are continuing to refine the model initialization/configuration necessary to provide the high-resolution (1 km) MM5 model simulations to be used in this project. Currently, the MM5 is configured with 62 vertical sigma layers with the lowest computational layer at 30 m AGL and 50-m layer spacing up to 2 km AGL, and the remaining 23 layers distributed with decreasing resolution to the model top at 50 hPa. Depending on the type of case, we may choose to modify the MM5 vertical layer distribution.

We are currently creating the model initial conditions and boundary conditions for several types of meteorological cases over the ARM-CART site during July 1997. These include the relatively clear-sky case used above as a benchmark (July 12 1997), a case with predominantly shallow convection and no precipitation (July 6 1997), a case with shallow convection transitioning to deep convection and precipitation (July 10 1997), and a frontal-passage case (July 14 1997). The high-resolution MM5 model fields for these cases will provide many different types of cloud fields for testing of the gamma weighted two stream radiative transfer model and provide control simulations for future experiments using this radiation model directly within the MM5.

We anticipate finishing an evaluation of the gamma-weighted two stream model by the end of the second year (if we can obtain sufficient 1-km resolution MM5 cloud data) and implementing the gamma-weighted two stream within MM5 during the third year with sensitivity tests performed for the July 1997 case study period.

6. Captions for Accompanying Attached Figures

7. Publications

Publications (Refereed, in Print)

Babb, D.M., J. Verlinde, and B.A. Albrecht, 1999: Retrieval of cloud microphysical parameters from 94GHz radar power spectra, *J. Atmos. Oceanic Technol.*, **16**, 489-503.

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Liljegren, J.C., E.E. Clothiaux, G.G. Mace, S. Kato, and X. Dong, 2000: Retrieval of cloud liquid water path. *J. Atmos. Oceanic. Technol.*, Submitted.

Mace, G.G., E.E. Clothiaux, and T.P. Ackerman, 2000: The composite characteristics of cirrus clouds: Bulk properties revealed by 1 year of cloud radar data. *J. Geophy. Res.*, Submitted.

Marchand, R.T., T.P. Ackerman, and E.E. Clothiaux, 2000: A cloud climatology for the Southern Great Plains, *J. Geophy. Res.*, Submitted.

Min, Q., L.C. Harrison, and E.E. Clothiaux, 2000: Joint statistics of photon pathlength and cloud optical depth: Case studies. *J. Geophy. Res.*, Submitted.

Publications (Non-Refereed, to the ARM Infrastructure)

Clothiaux, E.E., and D.D. Turner, 2000: The Atmospheric Radiation Measurement Program Data Products: Data Files, Data Processing and Data Quality Technical Report for Users (An Unsolicited View from the Trenches).

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8. Conference Proceedings and Reports

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9. Publications (Relevant, Previously Published)

Clothiaux, E.E., R.S. Penc, D.W. Thomson, T.P. Ackerman and S.R. Williams, 1993: A First-guess feature-based algorithm for estimating wind speed in clear-air doppler radar spectra. *J. Atmos. and Oceanic Technol.*, **11**, 888-908.

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Miller, M.A., J. Verlinde, C.V. Gilbert, G.J. Lehenbauer, J.S. Tongue and E.E. Clothiaux, 1998: Detection of nonprecipitating clouds with the WSR-88D: A theoretical and experimental survey of capabilities and limitations. *Weather and Forcasting,* **13**, 1046-1062.